Alexandre Gustave Eiffel: An Engineer Scientist

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Eiffel is best remembered for engineering the tower that is a Paris landmark and bears his name. However, Eiffel has many other firsts to his credit. He was one of the first to experimentally obtain material properties of wrought iron that permitted him to proportion structural members in bridges and buildings that he built to sustain the service loads experienced by them. Having struggled to get a good estimate of wind forces on the many tall structures that he designed and constructed during his career, Eiffel was among the first to experimentally obtain data on fluid flow around an object and establish accurately the drag on a body dropped in air in his later years. He developed one of the earliest versions of the 'wind tunnel' that today plays a pivotal role in aerodynamic studies. This article traces the evolution of Alexandre Gustave Eiffel as an engineer and scientist.

Introduction

Alexandre Gustave Eiffel was born on 15th December 1832, in Dijon, Cote-d'Or France and died in 1923 leaving behind contributions across diverse fields. After his early schooling in science and arts, Eiffel graduated with a Masters degree in Chemistry in 1855 from the Ecole Centrale des Arts et Manufacturers in Paris, one of the best engineering schools of Europe. Though Eiffel set out to pursue the family's wine business, circumstances left him seeking career opportunities outside this discipline after completing his studies.

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The Industrial Revolution played an important role in Gustave Eiffel's life. England, France,Spain, Portugal and other European nations were colonizing parts of Africa, Asia and South America to obtain raw materials for their industries and seek new markets for selling finished goods. Development in transport infrastructure from the harbours to the hinterlands both within Europe and in the new colonies became vitally important. This rapid industrialization also led to developments of new technologies (the steam engine, the railways, post and telegraph, to name a few) and the discovery of new materials. Eiffel's work was greatly influenced by these conditions brought about by the Industrial Revolution, in particular, the area of transportation.

Development of railway and roadway infrastructure, and the need to cross a number of rivers and deep ravines in the mountainous terrains fueled a need for bridges. Eiffel gained a reputation as an engineer designing and constructing bridges which allowed him to pursue larger and more difficult projects later in life. The bridges that he designed were constructed all over the world.

While circumstances may have placed Eiffel in a domain that lay outside his basic training, he not only accepted this opportunity but also rose to the challenges that the situation warranted. Eiffel began his career at the construction site of a railway bridge project and committed himself to follow up on every detail of project management. This included basic tasks like scheduling, and inventory control, in addition to comprehension and interpretation of engineering design drawings and documents to the extent of taking decisions in changes needed when necessary. Such diligence rarely goes unnoticed and Eiffel soon found himself in other bridge construction projects that demanded management and engineering skills. During this process of field level learning, Eiffel kept himself informed of developments from around the world in the area of bridge engineering. His peers, the Roeblings, father and son pair of John and Washington had constructed the Ohio River Bridge in the late 1850s, and were poised to construct the Brookline Bridge (completed in 1887). Eiffel learnt that in the Ohio River project labourers had to spend extended periods of time in pressurized chambers at a great depth below the river bed due to difficulties encountered in excavating and sinking operations for caissons (well foundations – A thick cylindrical tube having solid base and a compacted infill material that is capped at the top providing support for the columns/piers of the superstructure). When the labourers came out too quickly they developed severe pain that came to be known as "diver's bends" caused by nitrogen bubbles getting trapped in the blood stream. Special chambers with gradually reducing levels of pressure had to be established at various intermediate depths, where the labourers spent time to stabilize the oxygen and nitrogen content in their blood stream. While time required for construction plays a role in the overall economics of the bridge, Eiffel realized that innovation in construction practices, and choices leading to simplifications in design that resulted in ease in construction with less skilled labour forces played an important role in realizing the overall objectives of the project. This view manifested itself in all the construction projects he undertook.

While Eiffel's initial design and construction work was on bridges (Viana Bridge, Portugal;

Tan An Bridge in Cochin, China; Garonne Bridge; etc.), he also engineered train stations (Pest, Hungary; Austerlitz railway station, Austria), Nice Observatory, commercial structures (Bon Marche department stores, Paris), religious structures (Church of Notre Dame des Champs in Paris, Synagogue des Tournelles Paris and others in Chile, Mexico and Africa), portable bridges for the army, and exhibition structures (Paris Universal Exposition of 1878).

Bridges

Having honed his skills in various bridge construction projects as an employee, Eiffel broke away and established a consulting and construction firm in collaboration with a Belgian engineer, Théophile Seyrig. Eiffel was not just savvy in construction management, he kept himself informed on scientific and engineering developments that took place and did not hesitate to apply the knowledge gained when necessary. He was aware of developments in the mechanics of materials (Hooke in the 1650s, Young in 1807 and others) as will be illustrated later in this article; he was aware of contemporary developments in structural analysis – the method of forces by Maxwell in 1864; and developments in the stability of structural elements (propounded by Euler in the 1750s and developed by others later). His confidence in himself and his partner Seyrig led to Eiffel successfully bidding to design and build a 160 m long railway bridge over the river Douro, connecting the cities of Oporto and Vila Nova de Gaia in Portugal.

The proposal was the winner because Eiffel placed emphasis on arriving at simple-cost effective designs. Eiffel was aware that wind would contribute to substantial loads if solid structures were built. He therefore proposed a transparent structure! A truss, that would permit most of the wind to flow through it and result in reduced loads and consequently to a less expensive structure. Moreover, the design incorporated the newly-developed method of forces for structural analysis offering a more accurate estimate of the member forces. A double-hinged arch bridge (span 352 m, rise 62 m) with pillars rising out to support the deck was the outcome (*Figure* 1). This bridge was built in less than two years (5 January 1876 to 4 November 1877) because of Eiffel's project management

Figure 1. The Maria Pia double hinged arch bridge over the Douro River, Portugal.
http://en.wikipedia.org/wiki/Maria_Pia_Bridge

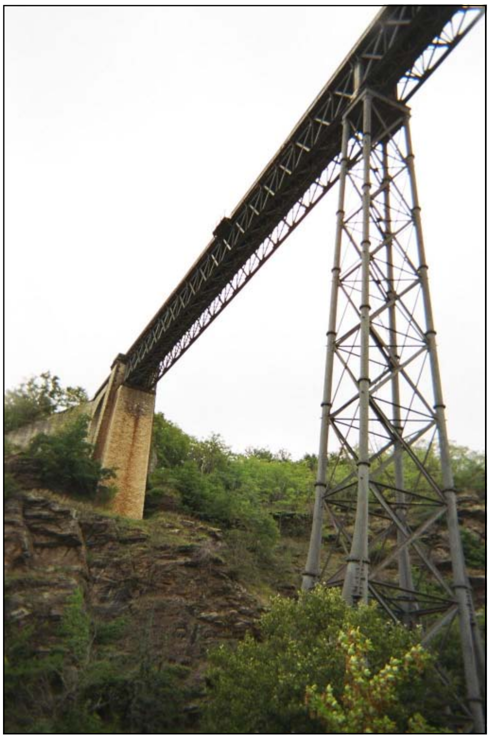

Figure 2. The Maria Rouzat Viaduct over the Sioule River, France.

http://en.wikipedia.org/wiki/Gustave_Eiffel

skills that were augmented by simplicity and elegance in the overall design. It was inaugurated by Queen Maria Pia and was named after her as Ponte Maria Pia.

Eiffel built a number of cast iron railway bridges in the Massif Central, such as the viaducts at Rouzat (*Figure* 2) and Bouble. It was during his micro management of these bridges that Eiffel stepped in and introduced modifications and improvisations in construction with the objective of securing improvement in connection details, reduction in construction time and an overall quality of the product. His knowledge of mechanics of materials convinced Eiffel that improvisations were essential in the cast iron bolted joints. So, he introduced modifications in the cast iron joint detail that improved its effectiveness considerably and eliminated flaws introduced during the fabrication process. Eiffel also improved the girder launching process that led to safe launching, thereby overcoming situations that previously led to pier overturning. This was accomplished by having a system of rollers on each support that could lock under loading conditions. Eiffel also designed and developed a system of hydraulic presses which allowed workers to set bridge pile foundations deep under water creating sturdy yet lightweight ‘web-like’ trusses and arches strong enough to withstand high winds. Moreover, this option did not need wells and caisson foundations in the bridges he designed, circumventing the problems encountered by the Roeblings.

Eiffel had a sound understanding of metal behavior which he used for producing structures that were large and beautiful and had novel elements in the design. He understood the advantages obtained from wrought iron’s strength and relative lightness that was lacking in cast iron and steel. This understanding of material strength to weight played an important role in later years while designing the Eiffel tower.

One of the important contributions made by Eiffel was his design of portable bridges (*Figure* 3). A set of coplanar triangular components placed next to each other and joined together formed the girder. Two such girders with plates fixed on top make up the bridge. Only three types of

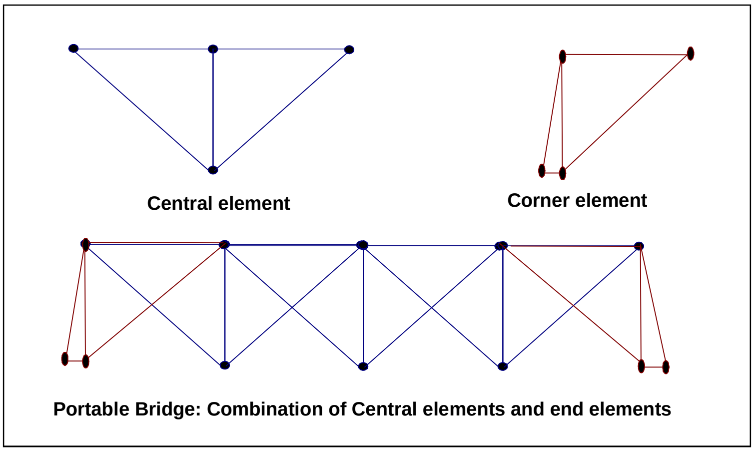

Figure 3. Concept of portable bridges.

elements are present in the structure – a horizontal element, a vertical end post and an inclined tie member. Two sets of triangular elements comprising of corner elements (red colour) and a set of central elements (blue colour) made in various dimensions and combined together result in the bridge girder (*Figure* 3). The bolting holes are pre-matched in the connecting members resulting in considerable ease in assembly. The advantage of this concept is that the connections are bolted, so they can be dismantled and re-assembled at different places; the material is light and can be transported and assembled with unskilled help, facilitating its deployment by diverse user groups.

Eiffel designed and constructed many bridges during the 1856–1890 period such as the Garonne River Bridge (his first project), Garabit Viaduct, Souleuvre Viaduct, Maria Pia Bridge, Long Bien Bridge in Hannoi (Vietnam), Coura River Bridge in Caminha (Portugal), Truong Tien Bridge over the Huong River in Hue (Vietnam), Quezon Bridge in Manila (Philippines), Railway Bridge in Constitucion (Chile).

One of his finest engineering accomplishments at that time was the Garabit Viaduct (*Figure* 4) built between 1880 and 1884. This was a railroad arch bridge spanning the Truyere River in the mountainous Massif Central region of France. The viaduct has an overall span of 565 m and a

Figure 4. Garabit Viaduct: railroad bridge.
http://en.wikipedia.org/wiki/Garabit_viaduct

principal span of 165 m. Wind effects continued to form the basis for Eiffel's designs and in turn he continued to discard the idea of a solid beam construction as its stiffness would attract very large forces besides enhancing the costs substantially. Instead, he adopted the concept of axial truss elements in the form of triangles to reduce wind forces as a large portion of the wind would blow through the openings. He concluded that truss structure provides greater stability when forces were equilibrated by a set of tension and compression segments formed in closed triangles. This approach reduced the effective unsupported length of compression members considerably and overcame local buckling problems in these elements as a consequence. Eiffel allowed the main deck to remain separated from the arch and instead modified the arch form to widen at the crown enhancing its beauty.

Statue of Liberty

One of Eiffel's smaller yet important works was the design he provided for the interior bracing system for the Statue of Liberty. The statue, meant to be a gift of the people of France to USA to commemorate the centenary of the American war of independence, was conceived as 'Lady Liberty' by French sculptor Frederic Auguste Bartholdi. The statue as visualized by the sculptor was to be 151 feet tall and having a 17 foot head. An 8 foot long index finger and an extended arm bearing the torch that was 42 feet long and 12 feet thick were other important features of the statue. Bartholdi recognized that a solid structure of this kind was not amenable for transportation in one piece. He approached Eiffel with the problem of developing a support system for this structure so as to withstand the wind forces and sustain its own weight, besides having a modular form that permitted transportation in a dismantled form to USA. Eiffel came up with the idea of an iron bolted truss skeleton to be encased in a hollow statue that was to be covered by a 3/32 inch thick copper sheet. The frame was supported on steel beams implanted in the granite pedestal so as to transfer the gravitational and lateral forces. In order to counterbalance the raised right arm causing an overhang load, Eiffel introduced supporting beams running through the body of the statue that connected with other beams anchored at the base and ran across to the extreme left. The Statue of Liberty was fabricated in France, dismantled, brought to USA and reassembled on Bedloe Island in New York City harbour in 1885.

Eiffel Tower

The Paris Centennial Exposition of 1889 was organized to commemorate the centenary of the French revolution. A 300 m tower was planned to mark this momentous occasion as it was thought to enshrine the values of 'Liberty, Equality and Fraternity' championed by the revolutionaries a hundred years earlier. Eiffel's company participated in the competitive bidding process and was awarded the contract for the tower construction. At that point in time, no structure that was 300 m tall had been built anywhere in the world. Eiffel recognized that the wind loads that the built structure would experience would be tremendous; the lack of information on the nature of wind forces and pressure distribution over such heights led him to consider lattice-trussed piers with incurving edges based on his experience with bridge design and construction as a possibility for such a tower.

Drawing on his earlier experiences, Eiffel knew that cast iron was brittle and lacked tensile strength, and was suitable, like stone, only when subject to compressive loads such as in arches and piers. Steel on the other hand was very elastic and he concluded that this would lead to considerable sway. His deep understanding of wrought iron made him believe that it was easy to work with and was strong and rigid enough to withstand the elements. Eiffel had determined the modulus of elasticity of wrought iron following the methods proposed by Robert Hooke and Thomas Young, pioneers who had propounded the theory of elasticity and had obtained properties of several metals. This scientific approach helped Eiffel in understanding dispersion of loads through structural elements that had different forms which eventually helped him in identifying a structure that was both aesthetically pleasing and was optimal (i.e., resulted in uniformly stressed members).

The odd angles of the individual members (*Figure* 5) in the tower

Figure 5. The intricacy of the member connections – view of the base arch; view of the corner; and an upward view of the tower from the inside.
Author's personal collection.

not only precluded the possibility of mass-producing these members, but also imposed considerable demand on drawing details for each member so that they could be fabricated and fitted on site with ease. The tower's curved weight-bearing edges created irregular arcs and the trusses in the numerous panels varied gradually from bottom to top. Every piece had to be designed separately, accounting for the inclination of the columns and braces, and all bolt holes were marked and made to precision. The elevator system to transport people to the top was yet another challenge. As a vertical shaft through the centre would destroy the beauty of the tower, Eiffel mandated that different elevators would rise at angles at the edges of the tower and in stages. Despite these challenges, Eiffel completed the tower [1,2,3] project ahead of schedule and 6% under budget.

Aerodynamics

In addition to his many engineering accomplishments, Eiffel had a scientific temperament and it was his scientific quests that led him to his pioneering aeronautical research. Eiffel's bridge design career had exposed him to the numerous problems posed by wind loads experienced by structures. Lack of a scientific basis had forced him and other contemporary designers to adopt large load factors to derive margins of safety with an increase in overall cost. His desire to resolve the uncertainty surrounding the forces experienced by bodies exposed to wind over a large height motivated him to pursue research in wind engineering. He started with tests performed from the first stage of the Eiffel Tower by using a specially designed dropping machine [4] which recorded the aerodynamic characteristics of bodies that were added as appendages to it. The data obtained from these tests provided information on the drag resistance offered by the wind to floating bodies, besides offering insights into the pressure distribution on the object. The existence of a pressure reduction, suction, on the downstream side of the bodies was an important finding from the study. But Eiffel realized that they needed to be substantiated through more refined experiments. Eiffel built his first wind tunnel at the foot of the Eiffel Tower in 1909 [4]. The test section of his first wind tunnel was 1.50 m in diameter and the blower was installed downstream allowing a satisfactory flow in the test section. The section was large enough to test full models of airplanes and create a wind velocity of 20 m/s approaching conditions close to the real flow. He systematically repeated most of his studies on flow around solid objects at various orientations in order to test the validity and quality of the results in the wind tunnel and confirm the correctness of his data obtained from the drop tests conducted in 1903.

Eiffel built a new wind tunnel in Auteuil near Paris in 1912 at his own expense. The new facility had an increase in the test section size (2 m diameter), and could develop wind velocity that ranged between 30 and 40 m/s. He introduced modifications in the design of the tunnel by adding a contraction upstream and a diffuser downstream of the test section, to reduce the electrical power requirements for the facility but this modification also offered him twin test sections where different field conditions could be created. This wind tunnel came to be known in later years as the 'Eiffel wind tunnel'. His engineering accomplishments and reputation for scientific rigour resulted in a number of the aircraft inventors of that time seeking his expertise to assess the wing profile designs for the aircrafts they constructed. The importance of the contribution of Eiffel to aerodynamics in its early years was recognized by many institutions, including the Smithsonian Institution that awarded him the Langley Gold Medal in 1913. The French government has preserved Eiffel's wind tunnel as a national treasure to this day. In his book on the *History of Aerodynamics*, Anderson [5] has dwelled on Eiffel's seminal contributions to this field.

Closing Remarks

Eiffel was a brilliant engineer and scientist par excellence. The tower that bears his name received such worldwide accolade that his other precedent-setting works in bridge design and construction, and contributions to aerodynamics and telecommunication were overlooked by the public at large. Developments in the new field of radio transmission in the early part of the twentieth century were recognized by Eiffel and he established transmitters on the tower that played an important role during World Wars I and II. He also realized that meteorology could benefit from observations made from the tower and was a pioneer in this area. The magnificence of the tower attracted many engineers to marvel at its form and the inspired engineering that lay behind its construction. Weidmann and Pinelis [6] undertook a study on the form of the Eiffel Tower and concluded that the form had to do with "Eiffel's respect for wind loading".

Suggested Reading

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